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INFLUENCE OF MONITORING CONDITIONS ON THE STRESS WAVE EMISSION DATA RECORDED DURING TENSILE TESTING OF A GRP

G. D. Sims, et al

June 1979

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ABSTRACT

The stress wave or acoustic emission monitoring technique is a potentially valuable tool for the detection of failures in reinforced plastics. The monitoring conditions used may vary under different test circumstances and influence the actual data recorded. It is not yet possible to predict these effects from a basic understanding of the stress wave source event, its propagation and interaction with the detection system.

In this report the results of an empirical study of these monitoring conditions using a practical test situation are reported. Repeat tensile tests have been conducted using a standardised procedure for a glass-fibre/epoxy laminate of low variability for several monitoring parameters such as system gain, transducer type, transducer to failure site separation distance, specimen dimensions, ringdown v. event and total count v. count rate.

Under most conditions a similar trend of emission data with increased applied stress was obtained. In some cases only the final failure was detected and in all cases there was a considerable variation in the absolute count levels recorded. It was found in several cases that simple empirical relationships could be obtained which allowed for these changes in the monitoring condition. However, the potential dangers in accepting data without undertaking calibration-type experiments and without directly relating the emission data to actual failures were clearly apparent. In particular, there is a need to establish that an absence of emissions is in reality an absence of failures.

1. INTRODUCTION

Detection of the stress waves emitted by failures in stressed materials is gaining recognition for both the evaluation of failure mechanisms and for the validation of components and structures (1). The technique shows particular promise for composite materials, which are 'noisy' and often include non-catastrophic microfailures amongst the different failure mechanisms. It is noticeable that the reported stress wave emission (SWE) (alternatively referred to as acoustic emission) experiments have used a variety of commercial and in-house monitoring and processing equipment with a variety of gain settings, frequencies, bandwidths etc. Consequently, comparison of results obtained by different workers is rarely possible. Even within one laboratory, changes may occur involuntarily due to developments in the equipment or be enforced by changes in material, available specimen size, background noise levels, method of stressing etc.

To predict theoretically the effects of different monitoring conditions requires an understanding of the character of the source emission and its interaction with the material and geometry of the specimen, the coupling medium and the transducer. This is a very difficult problem, and present experimental research employs idealised specimen geometries dissimilar from normal specimens and structures (2). The associated problems of absolute calibration of transducers, and reference standards are under discussion by several working groups for Acoustic Emission including the British Group. Methods are being developed for the calibration of transducers against a reproducable source signal (3) but transposition to real test situations is less easily accomplished.

In this report, the results are given of an empirical evaluation of the effect of several monitoring parameters on the stress wave emission data

recorded during tensile testing to failure of a glass-fibre fabric/epoxy laminate. The parameters considered were transducer to failure site distance, system gain, transducer type, specimen dimensions, ring-down v. event counting and total count v. count rate. The repetative tests were conducted on a servo-hydraulic test facility. This was not the optimum equipment for low background noise but it was to be used for fatigue tests on the same material as part of a programme concerned with the detection and assessment of micro-damage in reinforced plastics (4 - 6).

2. EXPERIMENTAL PROGRAMME

2.1 Specimen Preparation and Mechanical Test Procedure

Specimens were prepared from 1220 mm by 1220 mm by 3.2 mm thick sheets of a hot-pressed glass fibre fabric/epoxy laminate (Permaglass 22 FE, BTR-Permali Ltd). The laminate contained 45% by volume of square weave fabric and negligible porosity. The laminate was cut with the two principle fibre axes at 0 ° and 90 ° to the specimen axis. To minimise machining damage, the specimen shapes given in figure 1 were prepared using fine grade, water cooled diamond blades and a 150 mm diameter diamond edge grinding wheel. Several specimen shapes were used as described later.

The mechanical test conducted each time was tensile at a displacement rate of 1 mm/min. using the crosshead drive facility on a 1250 Instron servo-hydraulic test machine, see figure 2. Hydraulic grips, see insert figure 2, ensured reproducable and adjustable grip pressures. Strain was measured on type A specimens using a ± 10% 25 mm gauge length Instron clip-on extensometer. Applied load, crosshead displacement (or strain) and SWE data were recorded continuously on a built-in multiple-pen servo chart recorder. Normally three to four specimens were tested for each test condition. The full test programme is given in section 3.

2.2 Stress Wave Emission Equipment

The detection and processing of SWE signals was by ACEL 105

processors (Acoustic Emission Consultants Ltd), figure 3. This equipment, consisting of the main unit and a fixed 40 dB preamplifier, was completely self-contained, portable (including battery power) and retained a degree of flexibility while being cheaper and simpler than modular equipment. Hence it has potential as a standard system suitable for further simplification for quality control testing, as envisaged by a prototype miniature NPL unit (6).

The different monitoring conditions were selected by push-buttons. The system gain could be set, including the 40 dB preamplifier (either differential or single ended depending on the transducer), from 40 dB to 105 dB in 1 dB increments. The frequency bandwidths available to match the transducer characteristics were, A - 20kHz to 100kHz, B - 100kHz to 300kHz, C - 300kHz to 1MHz and D - 1MHz to 2MHz. If none of these ranges were selected the processor operates over the full bandwidth.

In addition to facilities for the calibration and scaling of the 10 volt DC output, a clock activated re-set allowed the counts per time interval, variable from 0.1 seconds to 10 minutes, to be obtained. An additional module (LID 305) enabled the counter to be reset by incremental, one hundredths of a full scale variable from 1 to 10 volts DC, increases in the load or other DC signal.

It was possible to operate the processor in either the ringdown or envelope counting modes. Envelope counting recorded each emission pulse, above the threshold voltage, as a single count or event, whereas, ring-down counting recorded each time the waveform within the pulse exceeded the threshold voltage and provided an arbitary weighting of the size of the pulse. Unless indicated otherwise the total count in the ring-down mode was recorded.

In these experiments the transducer was held to the specimen by a constant load spring with vacuum grease (Apiezon M) as the coupling medium. Preliminary trials showed that the loading spring would squeeze out excess grease to leave a 40 μm thick layer (NB 5 kg load spring for D 140 type transducer).

A wad of plasticine was placed around the lower end of the specimen, after tightening the grips, to reduce spurious emissions arising from vibration of the servo-hydraulic ram. The maximum gain used was that which produced less than 10 counts per minute from background noise when the test was fully prepared and allowed to stabilise following grip closure.

3. EXPERIMENTAL RESULTS

The experimental programme fell naturally into the three parts detailed below. The mechanical test was identical in all cases and the specimens chosen randomly except that within each analysis all the specimens were cut in one direction from the same sheet. This prevented the difference in strengths between the two principal fibre axes and the smaller differences between different sheets from influencing the results.

Part I

A prototype ACEL 105, under evaluation at NPL, was used for this part of the programme in combination with a D141 Dunegan-Endevco emission transducer (serial no. 07). Fixed monitoring parameters were B filter setting and ring-down counting.

(a) Effect of grip pressure and condition

The minimum grip pressure to fail type A specimens was determined by incremental increases in grip pressure until failure rather than specimen slippage was obtained. This was repeated for plain specimens and specimens with bonded end-plates (45 mm x 45 mm) of a soft aluminium or PTFE sheet. The end-pieces were bonded using Chemlock 304 (Durham Raw Materials Ltd) following surface preparation as recommended. SWE tests were then conducted at this minimum grip pressure + 50%, and + 200%, with the transducer positioned at the centre of the specimen.

The graphs of grip pressure against maximum load sustained were identical for the plain and aluminium end-plate grip conditions. The minimum grip pressure for specimen failure was 33 bars, resulting in test conditions of 50 and

100 bars. PTFE end-plates debonded or fractured allowing the specimen to pull out of the grips at all grip pressures.

The average total count, at 78 dB, for plain and aluminium grip conditions at both test pressures are given in Table 1. No significant variation in the count output from 1st emission to failure was recorded for the different test conditions. Consequently, the remaining tests were undertaken using the plain grip condition and 50 bars grip pressure.

(b) Effect of specimen variability

Prior to altering gain etc., the variability of the mechanical and SWE response for constant conditions was obtained using Type A specimens with a centre positioned transducer and a clip-on extensometer. A typical stress-strain response is shown by curve I in figure 4. There was an initial linear portion with an average Young's Modulus of 23 GN/m^2 followed by an increasing deviation from linearity, normally associated with micro-damage (5), resulting in an average Modulus at failure of 17.8 GN/m^2. Curve II shows the corresponding total SWE output at 84 dB gain using scaling of the SWE analogue output to maintain maximum sensitivity at all stages of the test. Curve III shows the data in the absence of scaling for a full scale deflection of 10^6 counts. This latter data is also shown expressed as the logarithmic count in curve IV. The first counts were recorded at a stress of 20 MN/m^2 (0.11% strain) and, at maximum display sensitivity, the counts increased rapidly with increased load. These counts are relatively insignificant compared to the avalanche of counts recorded in the final stage of the test. For GRP's, the earlier counts would be associated normally with non-catastrophic microcracking (e.g. interfacial or resin cracking) and the final burst of counts related to failure of the aligned fibres, and the resulting disintegration and separation of the fracture surfaces. Final failure was a flat, brittle type fracture perpendicular to the stress axis with only a narrow zone of visual damage. Failure tended to be assoc-

iated with the slight stress concentration remaining at the ends of the parallel section in Type A specimens.

As a practical material and test situation have been used in this work, attention must be given first to variations in the mechanical response of the specimen. The mean stress and coefficient of variation (C.V) are given at specified applied strains in Table 2. The C.V. varied from 7.6% to 10%. The mean stress at failure was 316.7 MN/m^2 with a lower C.V. of 2.3%. Corresponding data are also given in Table 2 for the total SWE count and the logarithmic total SWE count. High scatter was recorded for total SWE counts but the scatter associated with the logarithmic data, which has a more similarly shaped curve to the stress-strain curve, was much lower and essentially identical at failure with the scatter in the failure stress. In Table 3, the mean stress and strain,and associated C.V.'s,are given at different SWE count levels and at failure. As the stress measurements were least variable and easiest to obtain, they were used as the reference base for all further SWE data. A statistically significant sample of 26 specimens from a different sheet of material confirmed these results, with similar scatter for failure stress and strain, and less scatter for properties prior to failure. Log.-log. plots of SWE data v. stress or strain gave similar results with an almost linear region between 500 and 50,000 counts which may prove to be of value in investigations relating microdamage to the emission data.

(c) Effect of transducer to failure site separation distance

Tests were conducted at separation distances of zero, 12.5, 25, 37.5, 50 and 75 mm at 84 dB gain using Type C specimens. The specimen was designed with a continuous waist, to define fairly precisely the final failure zone, and one extended grip section to allow the transducer to be placed at varying distances from this zone.

The stress at different count levels for the six separation distances are given in Table 4. The small increments in distance studied resulted in

close proximity of the data, in particular at low count levels. Except for the zero position, there was a trend to higher stresses with increased distance for the same count level. A log.-log. plot of the total SWE counts at failure against separation distance produced a straight line of slope -0.82 as shown in figure 5.

(d) Effect of specimen gauge width

Tests were conducted on specimen types D, E, F and G with gauge widths of 4, 15, 25 and 35 mm respectively. The rectangular blank for these specimens was increased to 222 mm long to ensure that for all gauge widths the same grip area as used previously was available. Consequently, the unwaisted portion increased with increased gauge width. The transducer was positioned 50 mm from the centre of the specimen and a gain of 84 dB was used. In this series of tests and other tests where the transducer was not symetrically placed relative to the grips, the transducer was placed so as to be furthest from the grip attached to the hydraulic ram as a precaution against spurious emissions.

The log.-linear plot of SWE data against stress for the four specimen sizes are given in Fig. 6. Although the results are normalised for their different areas, by expressing them as applied stress, a single curve was not produced. The failure stress increased with decreasing gauge width and there was an increase in the stress for the initiation of emissions for the 4 mm wide specimen, which was reflected by a higher stress at the deviation from linearity. The counts at any absolute stress level or proportion of the UTS increased with increase in the gauge width.

Part II

In this part of the programme two ACEL 105 units were used simultaneously. The signal from the D 140 transducer (Dungan-Endevco, serial no. 145 - virtually identical to D 141-07) supplied with the second production ACEL 105

was fed via a tee-piece coupler to the two units. This coupler resulted in 6 dB signal attenuation and the quoted gains have been corrected. The pre-production unit was used with constant monitoring conditions to check the consistency etc. of the test, while the parameters under investigation were set on the production unit. The servo-hydraulic test machine was resited at this time resulting in an increased background noise level that limited the gain to a maximum of 76 dB. Type B specimens were used for the remaining test programmes, except section (g).

(e) Effect of system gain

Using ringdown counting, the control unit was set at 76 dB, while the variable unit was set at 76, 65, 62, 55, 45 and 35 dB. Additional identical tests were conducted at gains of 90 and 82 dB on a 250 kN static Instron using the electric motor driven crosshead and manual wedge action grips. When the two ACEL 105 processors were fed by the same signal at the same gain setting, the total counts were within 5% of each other and no difference in the variation of counts with applied stress could be detected.

Logarithmic counts are plotted in figure 7 for each of the six gain settings against stress, expressed as a percentage of the UTS for each set of tests. Typical stress levels are also given. Results are also shown in this figure for data recorded at 90 and 82 dB on the static 250 kN Instron, and the 84 dB data recorded earlier in the programme on the servo-hydraulic test machine.

For all gain levels above 55 dB the curves displayed a marked similarity. Increased gain levels resulted in increased counts at all stages including failure and a decrease in the stress for the first emission. At 45 and 35 dB emission were recorded only during the final 5% of the test, the region associated with the final failure.

(f) Effect of ringdown or envelope counting

Tests were conducted at 76 dB with the control unit in ringdown

mode and variable unit in envelope mode. The average SWE results for both these count methods are given in figure 8 as a function of applied stress. Both methods illustrate the same count trend with stress, with a slightly higher stress for initiation and lower counts at all stages for the envelope method.

(g) Effect of count rate or total count

The total count was recorded by the control unit while the variable unit recorded counts per time, for intervals of 1 s and 10 s for different batches of specimens. These tests were repeated using the load incremental detector unit (LID 305) using, in different test series, both load and strain outputs. In both cases the full scale of the detector unit was set to just greater than the failure voltages. Type A specimens were used for the test using the LID 305 module so that a strain output could be obtained.

The total SWE count and the SWE counts per 1 second time intervals are given in figure 9 for a typical specimen. The rapid rise in count rate at failure is clearly apparent. The results obtained for 10 second time intervals were similar but to a coarser scale. Count rate results using incremental increases in the applied load to reset the counter are shown in figure 10. Brief tests were conducted for both steps and cycling loading programmes. A typical step loading result is shown in figure 11.

Part III

In this part of the programme only the production ACEL was used.

(h) Effect of transducer type

Tests were conducted for a selection of emission and accelerometer transducers centrally positioned on B-type specimens. Single ended or differential preamplifiers and different capacity load springs were used as appropriate. In all cases the tests were undertaken using the highest gain that produced less than 10 counts per minute from background noise.

The filter setting was selected to match the transducer resonant frequency except for the broad-band S9201 transducer. The basic manufacturers' data for the transducers are given in Table 5.

Typical curves of logarithmic SWE counts against stress for each transducer are given in figure 12. The S9201 data is for a single test, as the original transducer was found to be faulty and only one specimen of this series remained for the repeat test on a new transducer. Tests on a second sheet of the same laminate but of later manufacture and slightly different specification (i.e. fire retardent grade) suggested that the result in figure 12 is the high count side of the mean behaviour. This later sheet produced fewer counts prior to the final failure.

All the transducers, except the B&K 4345, show the same trend with considerable variation in counts at a constant stress and some variation in the stress for the initiation of emissions. The B&K 4345 transducer only recorded emissions during final failure, in spite of the relatively high gain setting. Helium gas jet calibration from 100 to 1000 kHz were carried out by Dr G Green at the Admiralty Materials Laboratory for emission transducers and the 116 kHz resonant frequency accelerometer (B&K 4344). The relative level of counts recorded in figure 12 for the S9201, D140 and B&K 4344 transducers would be expected from consideration of the maximum sensitivities (S/N ratio) recorded in these calibrations and the system gain employed. The similarity of the D140 and D141 transducers was also confirmed, as can be seen from comparing figure 12 with figure 8 for the same gain.

4. DISCUSSION

The glass-fibre/epoxy laminate chosen for this programme was found to have a low scatter in tensile behaviour which made it suitable for use in a standardised but practical test situation. Low scatter has also been reported for this material in studies of the effect of test conditions on

the fatigue strength (7). The UTS of this material was particularly consistent.

The grip conditions did not appear to alter the emission behaviour. The plain grip had the advantage of avoiding spurious emissions arising from debonding of the end plates but increased the chance of emissions arising from the grip/specimen interface. No differences were noted in this work but the higher scatter associated with small numbers of counts renders the observations tentative. Exact correlations similar to that used in reference 4 directly relating microscopic (optical or electron) observation of microdamage to emissions must be undertaken to ensure that the recorded emissions are only due to microdamage formation or that microdamage does not occur without emissions being recorded.

The high scatter recorded for total SWE counts is not unexpected as the initial counts are most influenced by spurious emissions and at failure the near asymptopic shape of the SWE curve results in large variations in SWE counts for small changes in the failure stress. A plot of failure stress against total SWE count did show a trend towards higher counts at higher failure stress. Expressing the results on a logarithmic basis gave a much reduced and acceptable scatter in SWE data. The similarity of the scatter for the UTS and the total counts at failure is to be particularly noted.

There is a requirement to monitor the occurrence of the first microdamage as this is the basis of the design criteria in GRP pressure vessels (8) and observations based on a stress-strain curve are not wholly satisfactory. SWE techniques are one of the best potential methods for assessing microdamage failure conditions but detailed calibration and definitions of failure will be required in order to assess the significance of the indications of small amounts of microdamage.

The separation distance had a particularly significant effect on the total counts recorded. Attenuation of the signal was pronounced, and compared to

metals monitoring of larger specimens or structures, particularly for defect location by triangulation techniques, may need to take more account of this effect. The greater attenuation in GRP's of the higher frequencies (9) will distort the frequency spectrum when frequency analysis is undertaken, and may be responsible for the greater influence of the separation distance on the total count than on lower count levels if the final burst of emissions have a higher frequency content. To minimise these effects the transducer should be within 25 mm of the failure.

Analysis of the effect of specimen size is complicated by the changes in the material response. For these materials, microfailures are expected to occur throughout the stressed volume depending on the value of the applied stress. The different shapes of this set of specimens results in, for a maximum stress of 200 MN/m^2 on the narrowest section, a stress at the grip end of the waisted section of 22, 67, 111 and 154 MN/m^2 for specimen shapes D, E, F and G respectively. Therefore, as the gauge width was increased both the volume and applied stress in the remainder of the specimen increased, conditions which would be expected to increase the degree of microcracking and thus the emissions recorded as observed in these tests. In addition, a change in specimen geometry will alter the natural frequencies of the specimen and signal reflections.

The tests undertaken at different gain settings showed the wide difference that can be obtained in the recorded count levels. It was possible at low system gain to monitor only the emissions associated with final failure. Thus amplitude analysis may prove useful in elucidating the occurrence of different failure mechanisms and should be easier and cheaper than attempting a full frequency analysis. This data has been investigated further by plotting on logarithmic scales the ratio of SWE counts at different stress levels against the ratio of gains using the 90 dB gain and results as the reference levels. From figure 13 it is seen that there is a straight line

relationship that encompasses the data from both machines, excluding final failure. The data for final failure also behaves consistently but tends for the same change in gain to produce smaller changes in the relative number of counts. Linear log plots of the stress for the 1st emission against gain suggest that higher gain levels would not reduce the stress for the first emissions below approximately 10 MN/m^2. The variation of the voltage threshold level for counting with system gain would be expected to influence the count level. But consideration of the circuit characteristics will not allow the effect of gain on the stress for the 1st emission to be predicted when a threshold stress exists. The ratio of the ringdown counts and event counts throughout the tests was fairly constant at approximately 3. But at failure the ratio increased to between 4.4 and 6.0. This is in agreement with the results in figure 7 which also indicated that higher amplitude pulses were produced during the final failure.

The high proportion of the recorded counts occurring in the last 3% of the test was evident in the count per interval (either time or load) tests. The use of a time base is limited as it cannot be related directly to material behaviour. Load increment analysis is particularly useful for repetitive loading programmes. It is possible from this information to determine accurately the load for emission initiation, or for a critical count level. The data obtained for incremental increases in strain were very similar as this material was almost linear-elastic to failure. Strain increments would be preferred for a material exhibiting large extension at a relatively constant load. The results in figure 11 suggest that there is not the complete absence of counts on reloading to the same maximum load referred to as the "Kaiser effect". This is perhaps to be expected if microfailures occur on the previous loading cycle that result in a reduction in the stress bearing area, redistribution of stress due to viscoelastic effects and the creation of stress concentrations at crack tips; so that work softening rather

than work hardening occurs. Hence, on loading to the previous maximum load further damage must remain a distinct possibility. For example, a cyclic test conducted at 90% of the UTS produced 2,500 counts on the 1st cycle, a few hundred (200 - 600) on subsequent cycles and 7,602 cycles on the final (13th) cycle. It is possible to determine the load for recommencement of emissions and the number of counts recorded below the previously applied maximum load.

The selection of transducers tested gave, with one exception, similar trends for the emission data but varying critical levels (e.g. total count, stress at particular count levels). The S9201 was approximately 6 dB more sensitive in the total gain (i.e. system gain and transducer sensitivity) than the B&K 4344 or D140 transducers. The difference in total count levels was close to that expected from figure 13 for a 6 dB change in gain from 90 to 84 dB. Differences in these tests included the frequency bandwidth selected as well as the total gain.

5. CONCLUSIONS

There are two aspects to the results obtained in this work. The encouraging aspect is that for several of the monitoring conditions studied a similar trend for the emission counts during loading was obtained. In some cases (e.g. gain, separation distance) simple empirical relationships permitted some allowance to be made for the changed monitoring conditions but it is, of course, not possible to apply these corrections to data not recorded at all due to, for instance, insufficient gain. The disturbing aspect is that the absolute number of counts or critical stress levels for (say) the first emissions were highly dependent on the monitoring conditions. In severe cases such as large separation distances or extremely low gain levels the information is not only incomplete but may be completely lost.

These difficulties are particularly noticeable when considering critical levels of counts or stress such as the stress for 1st emissions as an indication

of the critical strain for microdamage. This stress varied from 11 to 60 MN/m^2 for different transducers excluding the one case when only final failure was detected, and from 12 to 320 MN/m^2 over a very wide range of gains. In addition these counts are most susceptible to spurious emissions. Thus it is important to directly relate recorded emissions to damage observed directly, or by an alternative method, before stating categorically that "no emissions mean no damage" or that "emissions mean damage".

Preferred conditions for satisfactory SWE results in descending order of importance are, accurate calibration of system and material response, consistent technique, maximum system and transducer gain (though this may limit the flat-band response) and the transducer positioned close to failure.

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TABLE 1. Effect of grip conditions on SWE counts, at 78 dB gain

Grip Condition	Grip Pressure Date	Total SUVE Count	Log Total SWE Count	U.T.S. MN/m^2
Plain	50 100	152,930 138,878	5.184 5.143	331.4 311.2
Bonded Aluminium	50 100	140,256 133,766	5.147 5.126	327.6 325.3

TABLE 2. Varability of stress and SWE counts (linear & log) at specified strains.

Strain Level	0.2	0.7	1.0	1.2	1.4	Failure
Stress MN/m^2 C. of V.	46 10	150 7.6	206 9.0	244 8.2	281 9.4	317 2.3
SWE Counts C. of V.	212 80	7,844 51.6	27,240 32.2	44,000 28.3	91,700 48.2	310,000 30.1
Log. SWE Counts C. of V.	2.2 16.7	3.98 3.1	4.41 3.5	2.8	4.92 4.2	5.48 2.4

TABLE 3. Varability of strain and stress at specified count levels

Count Level	1	100	500	1000	10,000	50,000	100,000	at failure
Strain % C. of V.	0.11 36	0.22 12.6	0.31 13.1	0.38 16.2	0.76 17.4	1.31 7.4	1.51 5.7	1.66 8.6
Stress MN/m^2 C. of V.	20 32.3	44 16.6	64 16.4	77 16.6	151 17.6	256 6.2	289 2.2	317 2.3

TABLE 4. Effect of source - transducer separation distance on stress level for specified counts.

Separation Distance mm (specimens)	Stress at Specified Counts. MN/m^2							U.T.S. MN/m^2	Total Counts x 10^3
	1	100	500	1,000	10,000	50,000	100,000		
0 (3)	14	35	52	61	134	213	232	239	183.6
12.5 (4)	18	31	47	59	124	210	228	249	191.9
25.0 (3)	21	35	48	62	131	215	234	240	143.4
37.5 (4)	21	31	49	59	132	233	-	247	88.4
50 (3)	21	39	56	66	141	243	-	243	64.2
75 (2)	24	35	57	67	152	-	-	236	47.2

	Type	Serial Number	Sensitivity	Resonant Frequency KHz	Weight grams	External Diameter mm	Gain Setting dB	Frequency Setting	Manufacturers
Emission Transducers	D1413	07	-85 dB*	225	38	25	76	B	Dunegan Endevco
	D1403	145	-85 dB*	220	26	20	76	B	"
	S9201	AA22	-86 dB*	Flat-band	50	25	75	None	"
Accelerometers	4334	393290	63.9 mv/g	48	31	14	69	A	B & K Limited
	4345	359299	5.47 mv/g	45	26	14	86	A	"
	4344	420363	2.98 mv/g	116	2.1	7	89	B	"
	8307	417130	1.69 mv/g	75	2.3	6.5	80	A	"
	AQ40	D7331	24.7 mv/g	36	31	12.5	76	A	Environmental Equipment
	AQ5	E7019	3.5 mv/g	66	22	12.5	88	A	"

TABLE 5 - Transducer Characteristics and Experimental Settings

* ref 1 volt per microbar.

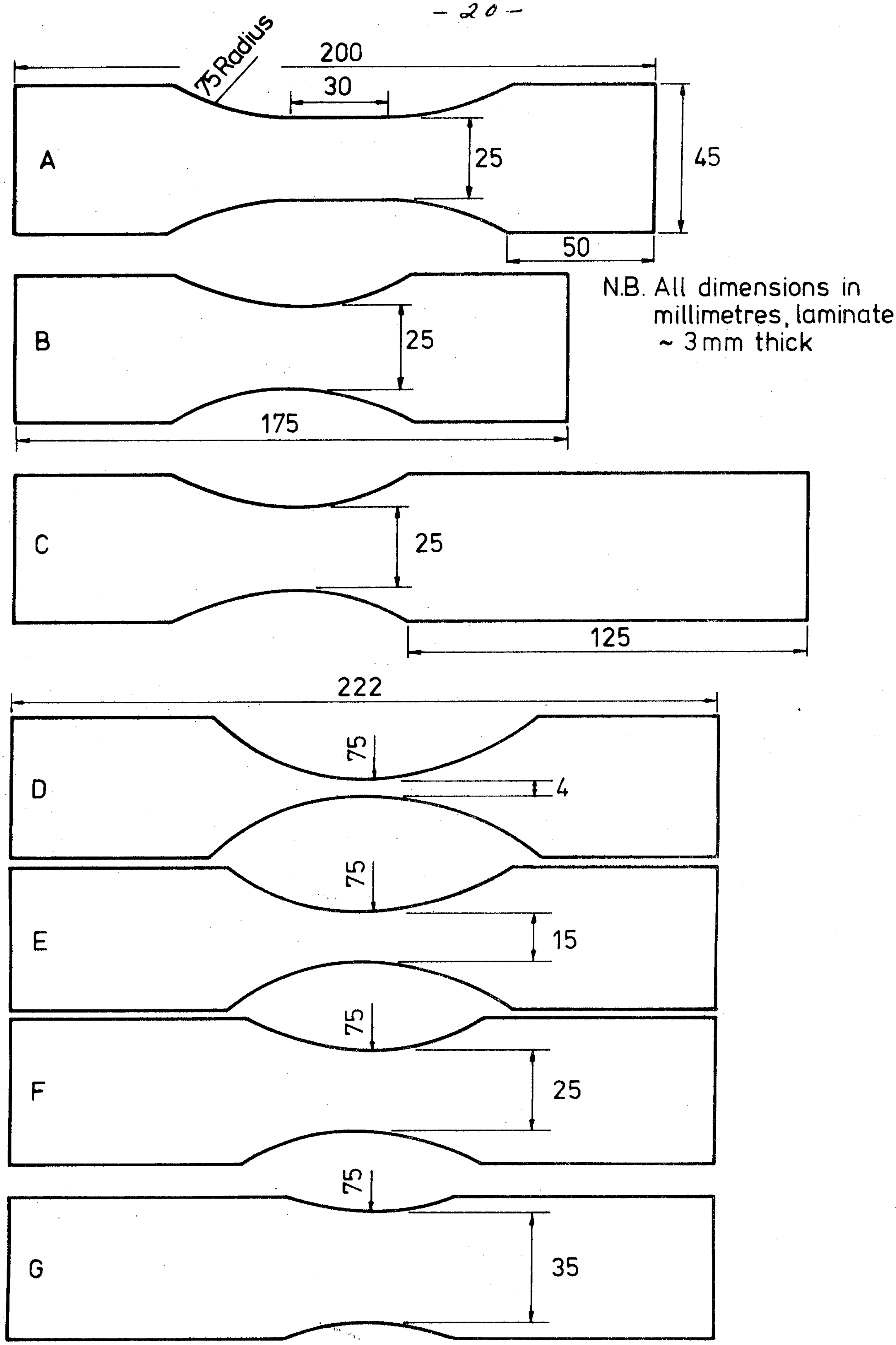

Fig.1 Specimen types and dimensions

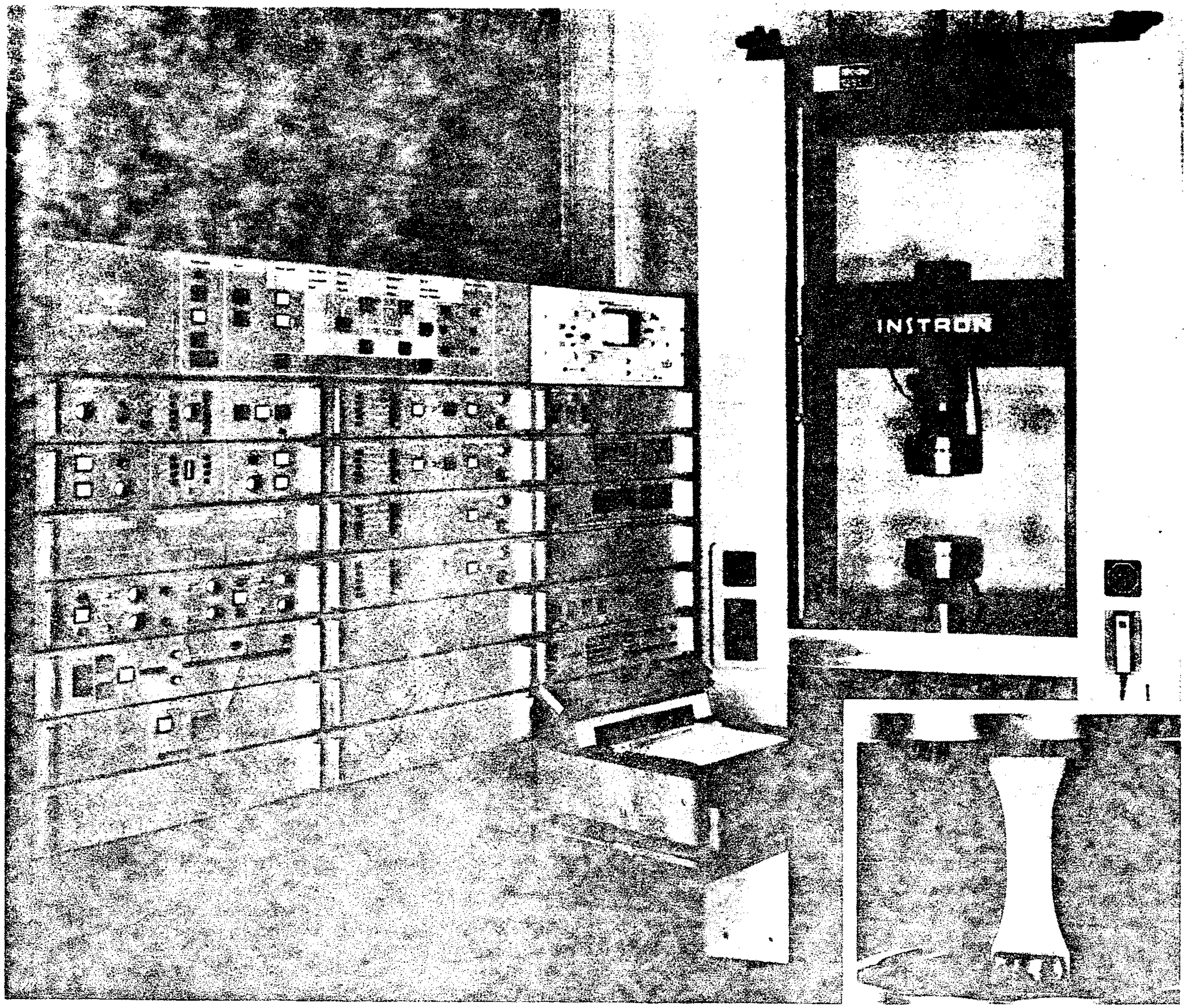

FIGURE 2. 1250 series Instron servo-hydraulic test machine. Insert, shows a Type A specimen mounted in the hydraulic grips.

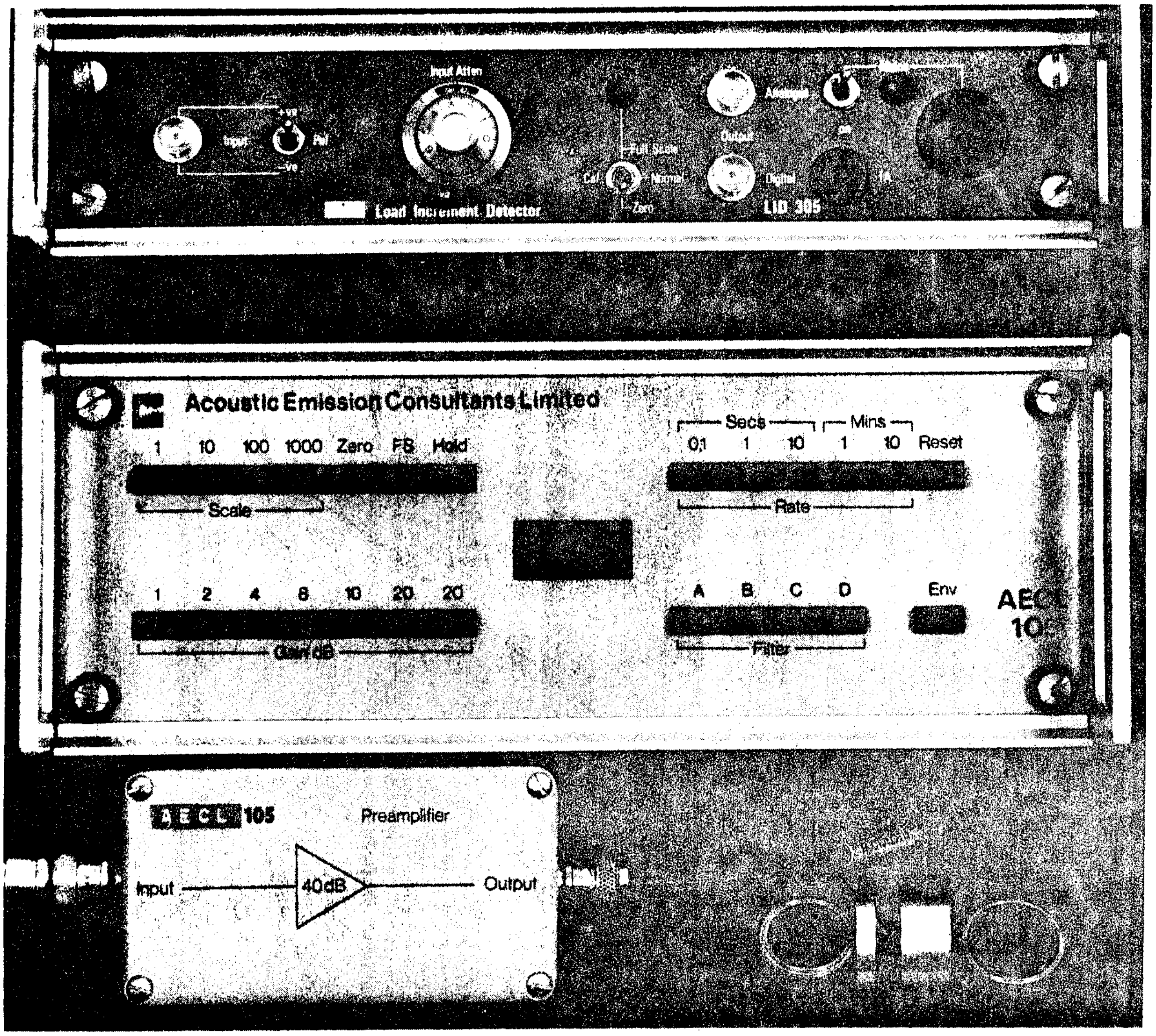

FIGURE 3. Stress Wave Emission equipment; ACEL 105, pre-amplifier, D141 transducer, constant load spring and LID 305.

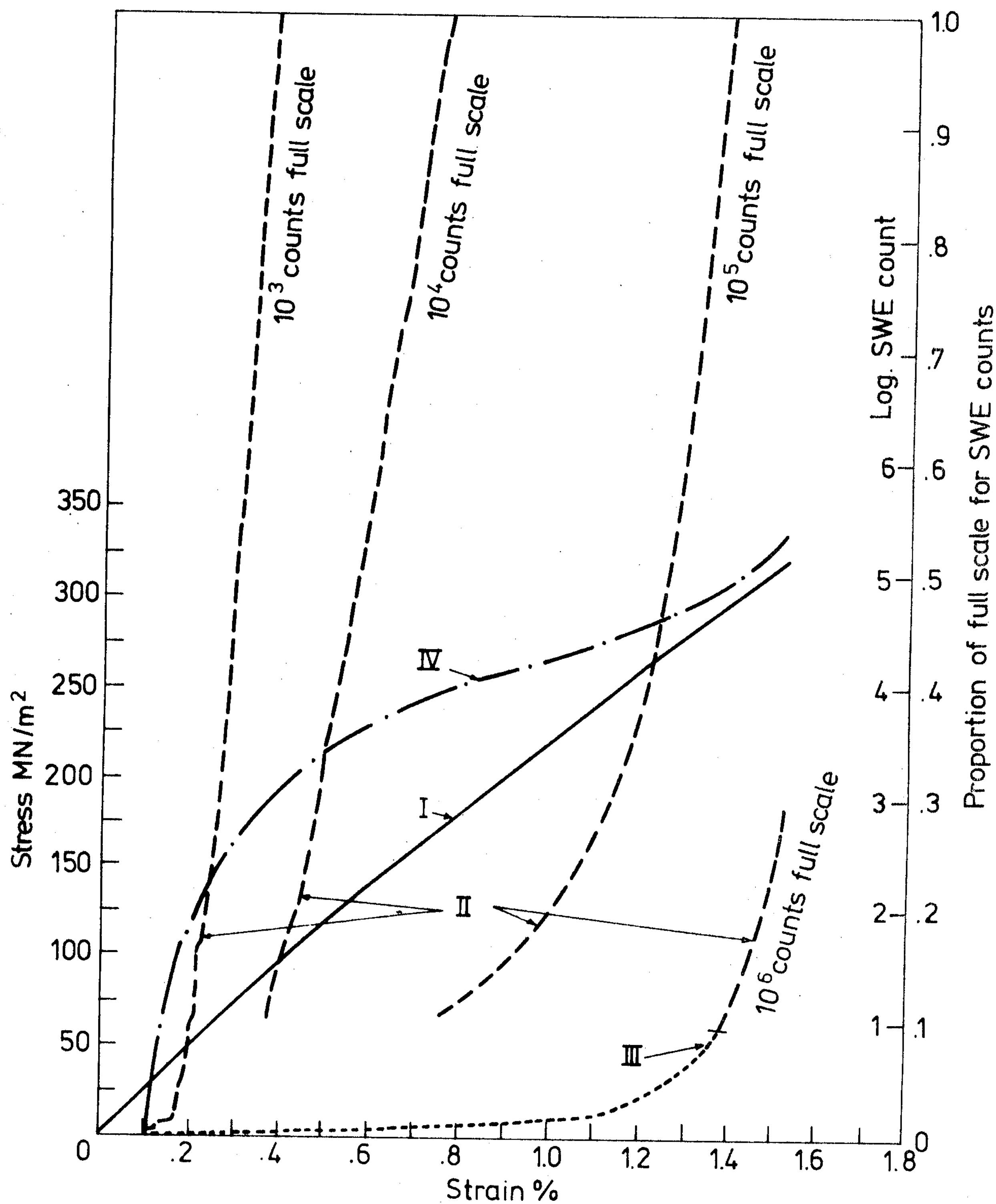

Fig. Stress - strain curve showing linear (scaled and unscaled) and logarithmic SWE counts

I Specimen stress-strain curve

II SWE counts (max sensitivity)

III SWE counts (min sensitivity)

IV Logarithmic SWE counts (min sensitivity)

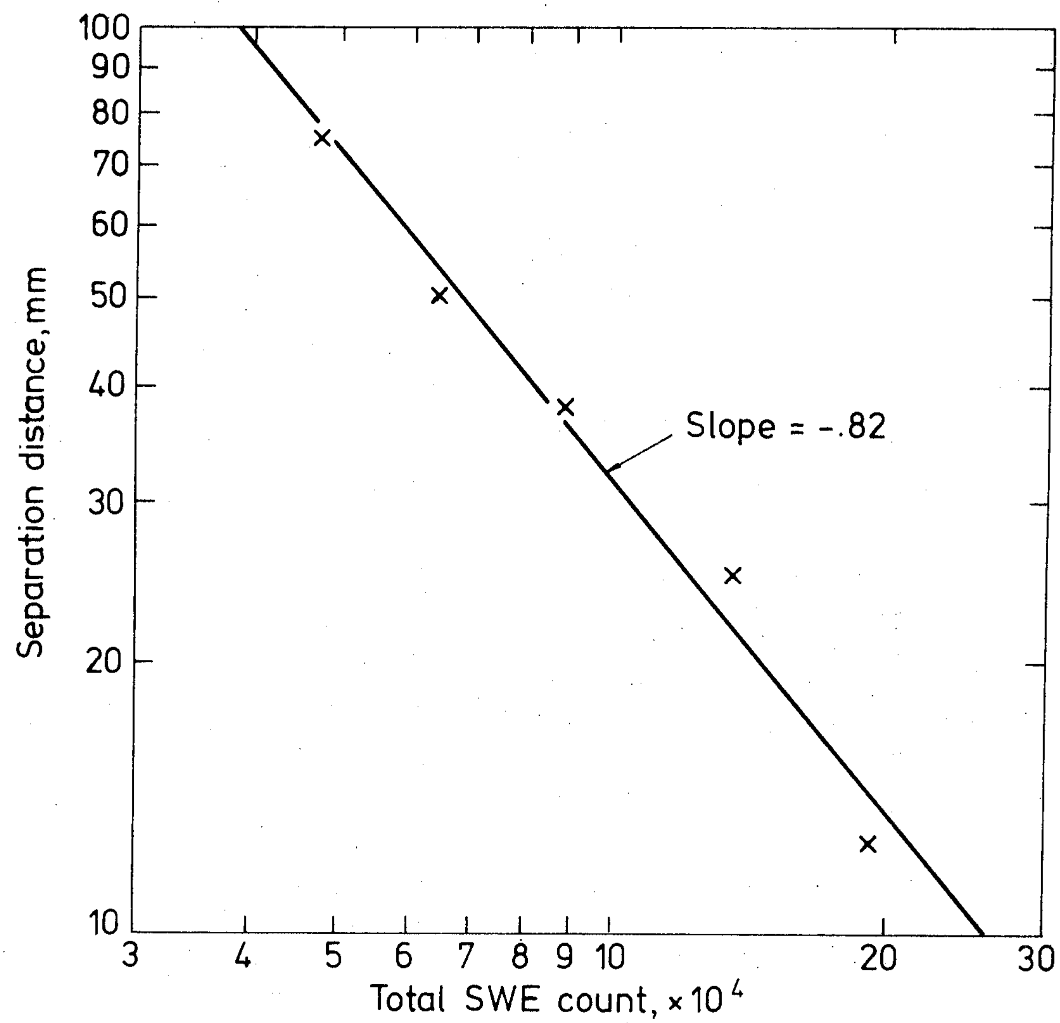

Fig.5 Variation of total SWE count with separation distance between failure site and transducer

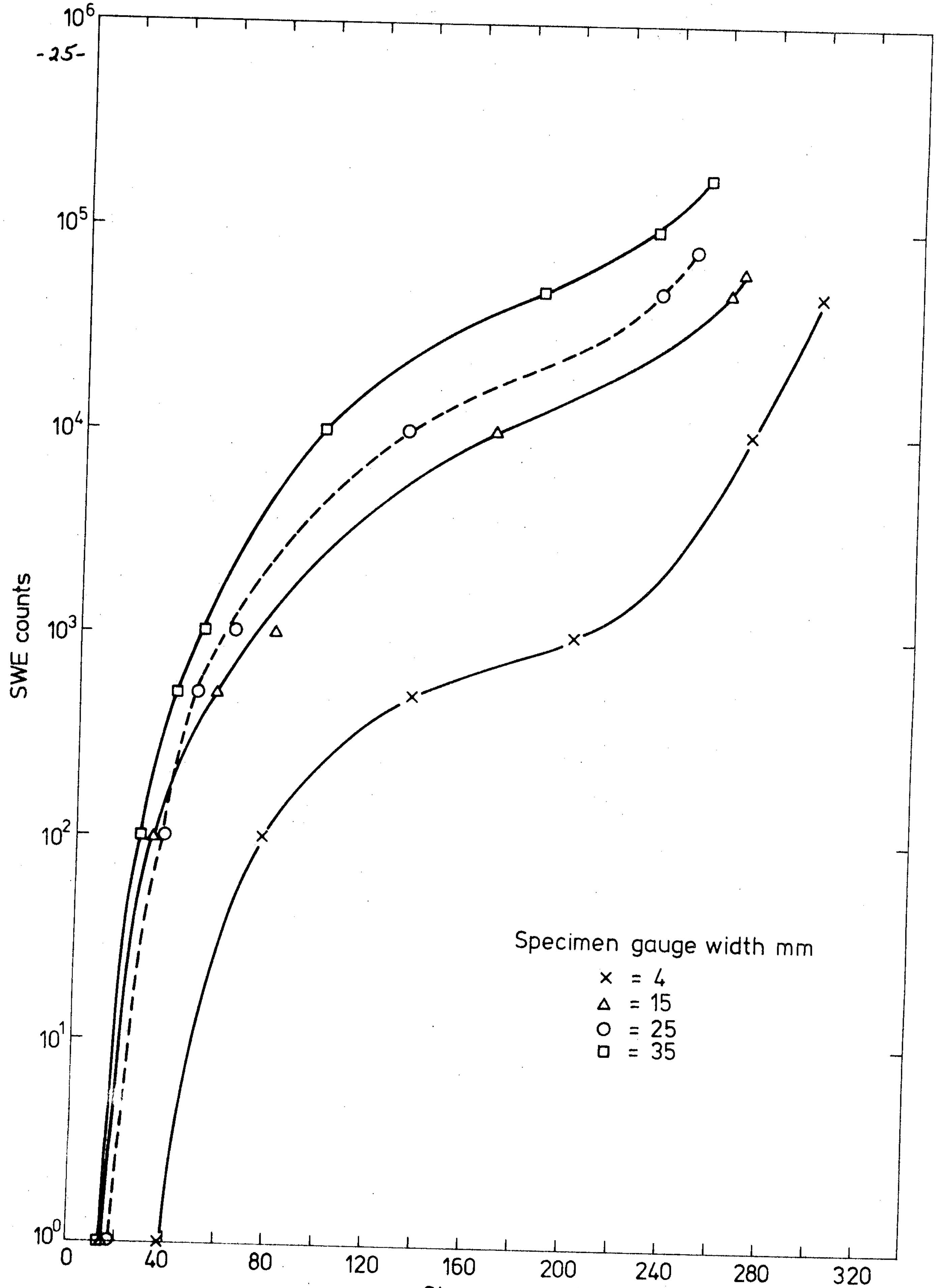

Fig.6 Effect of gauge width on SWE counts as a function of stress

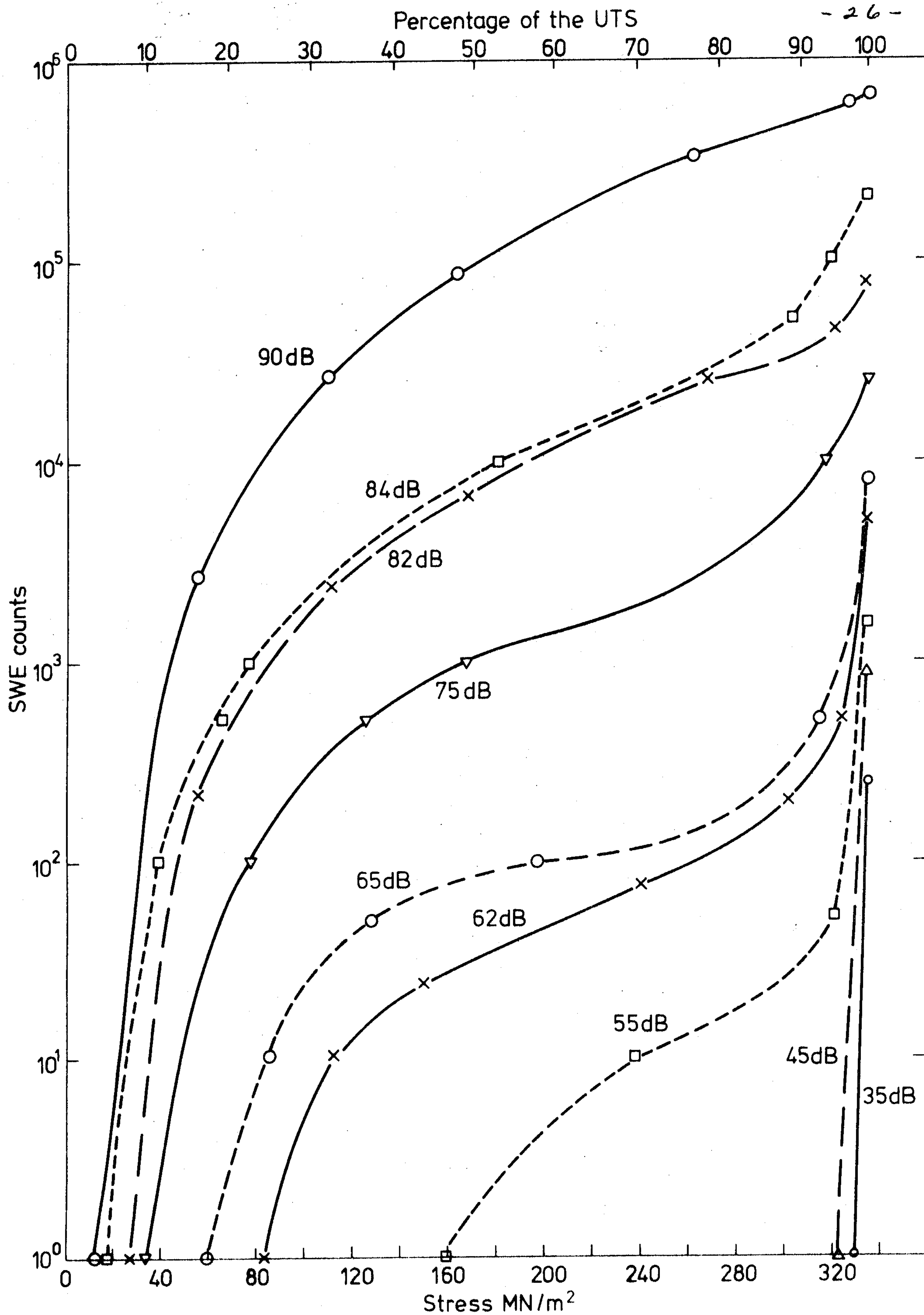

Fig.7 Effect of gain on SWE counts as a function of stress

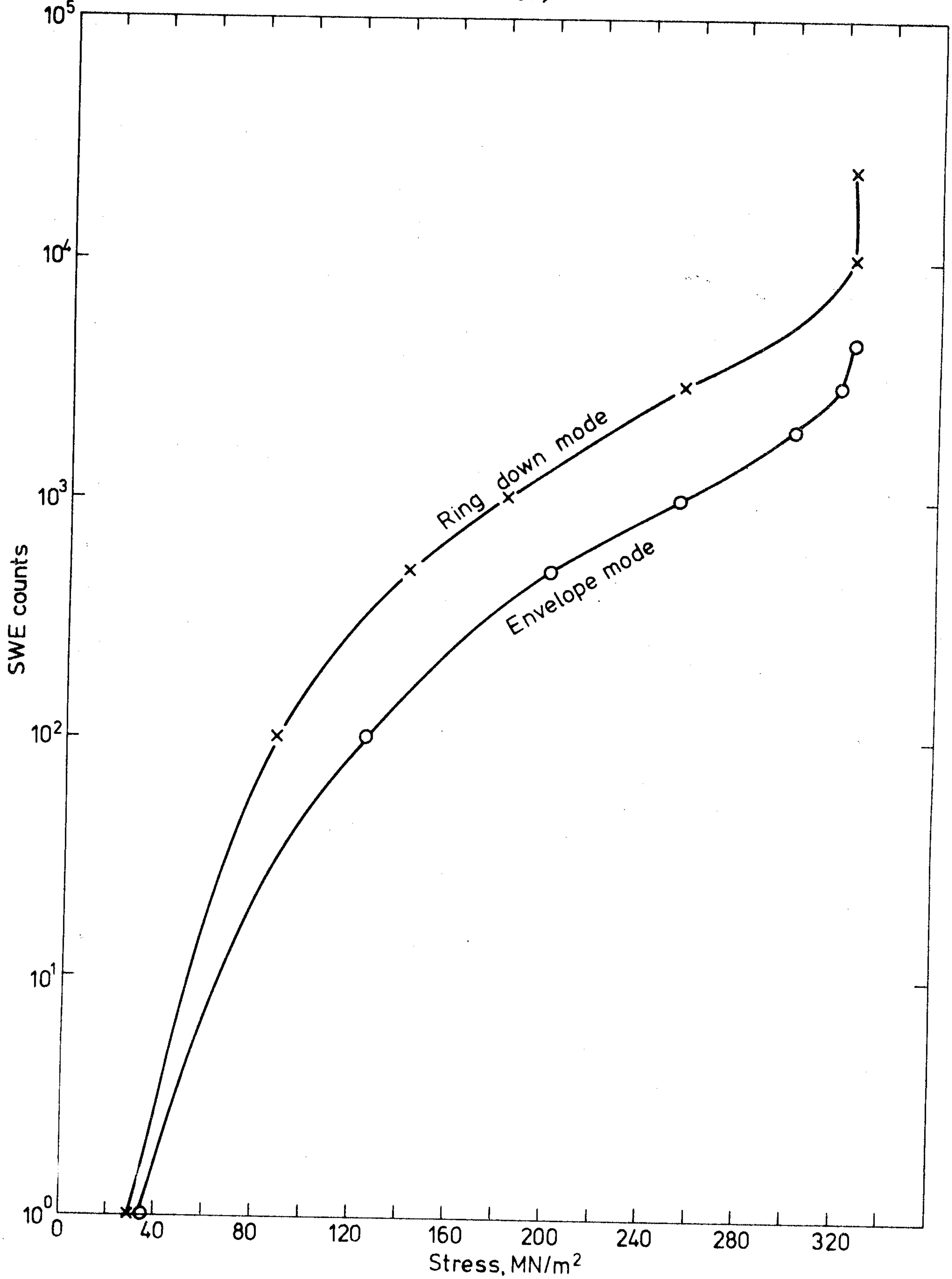

Fig.8 Comparison of outputs obtained from ring down and envelope counting modes

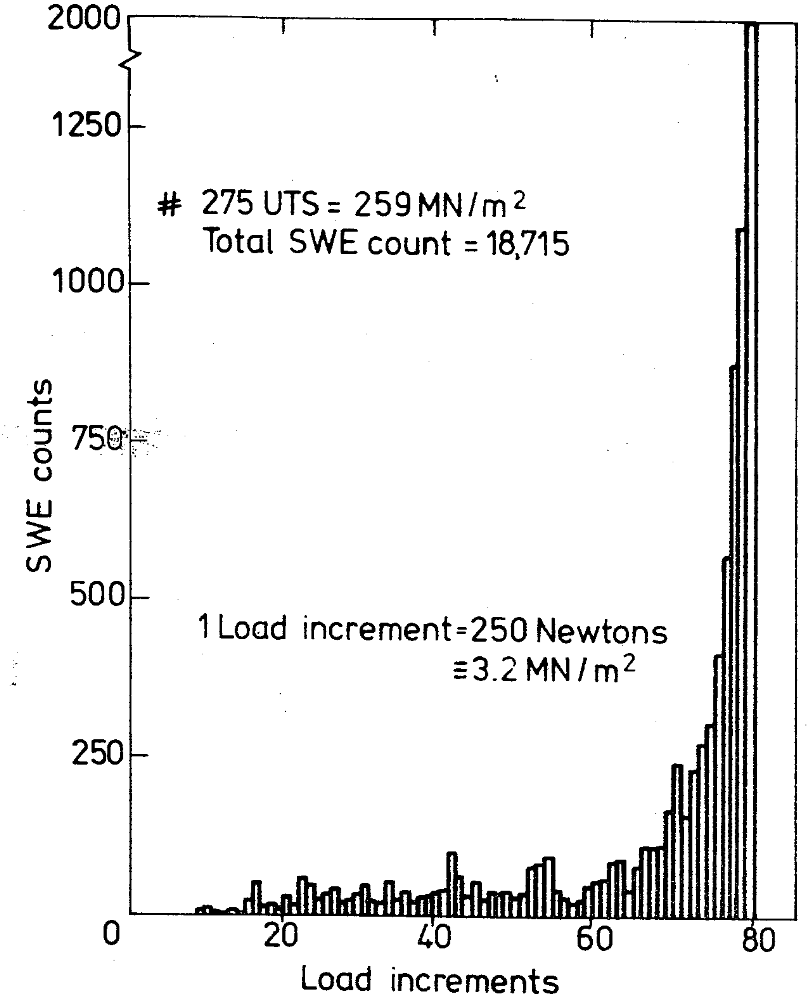

Fig.10 Counts per load increment for standard tensile test

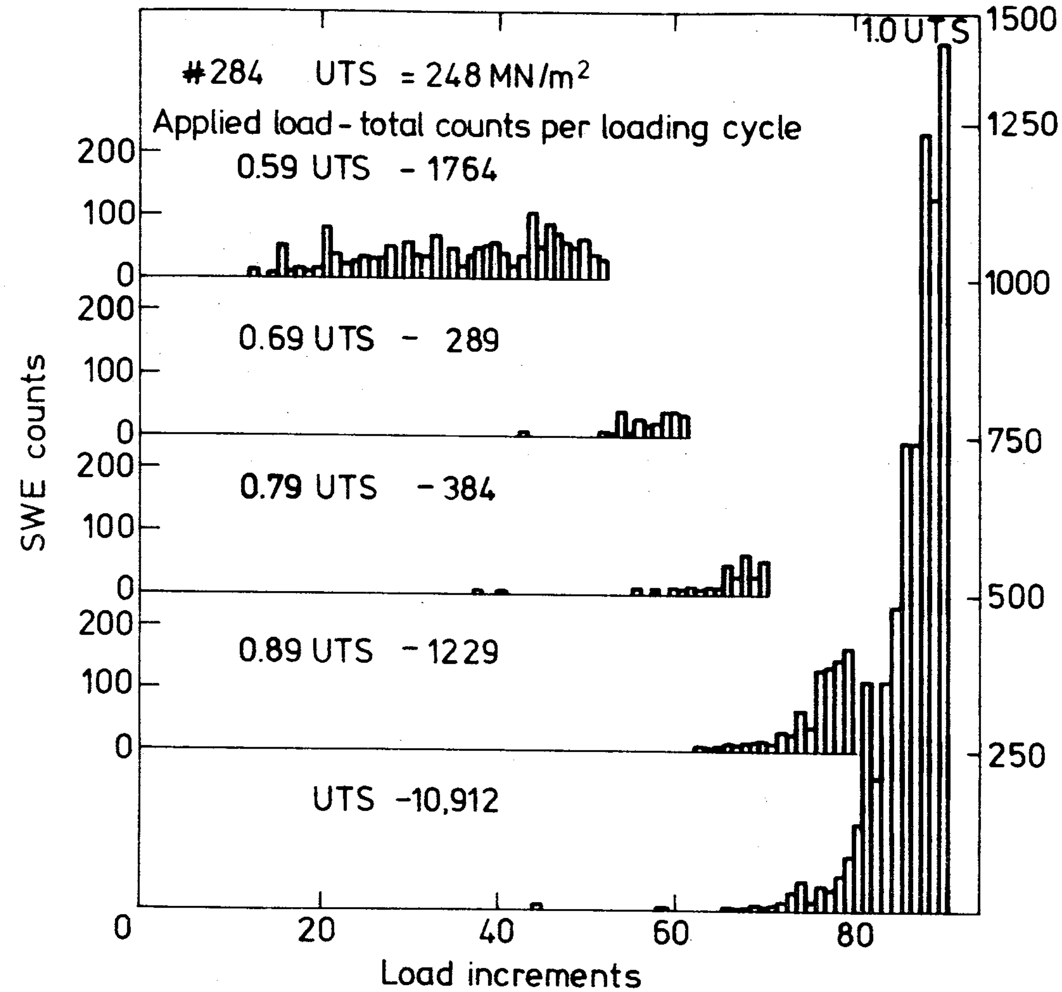

Fig 11 Counts per load increment for step loading to failure

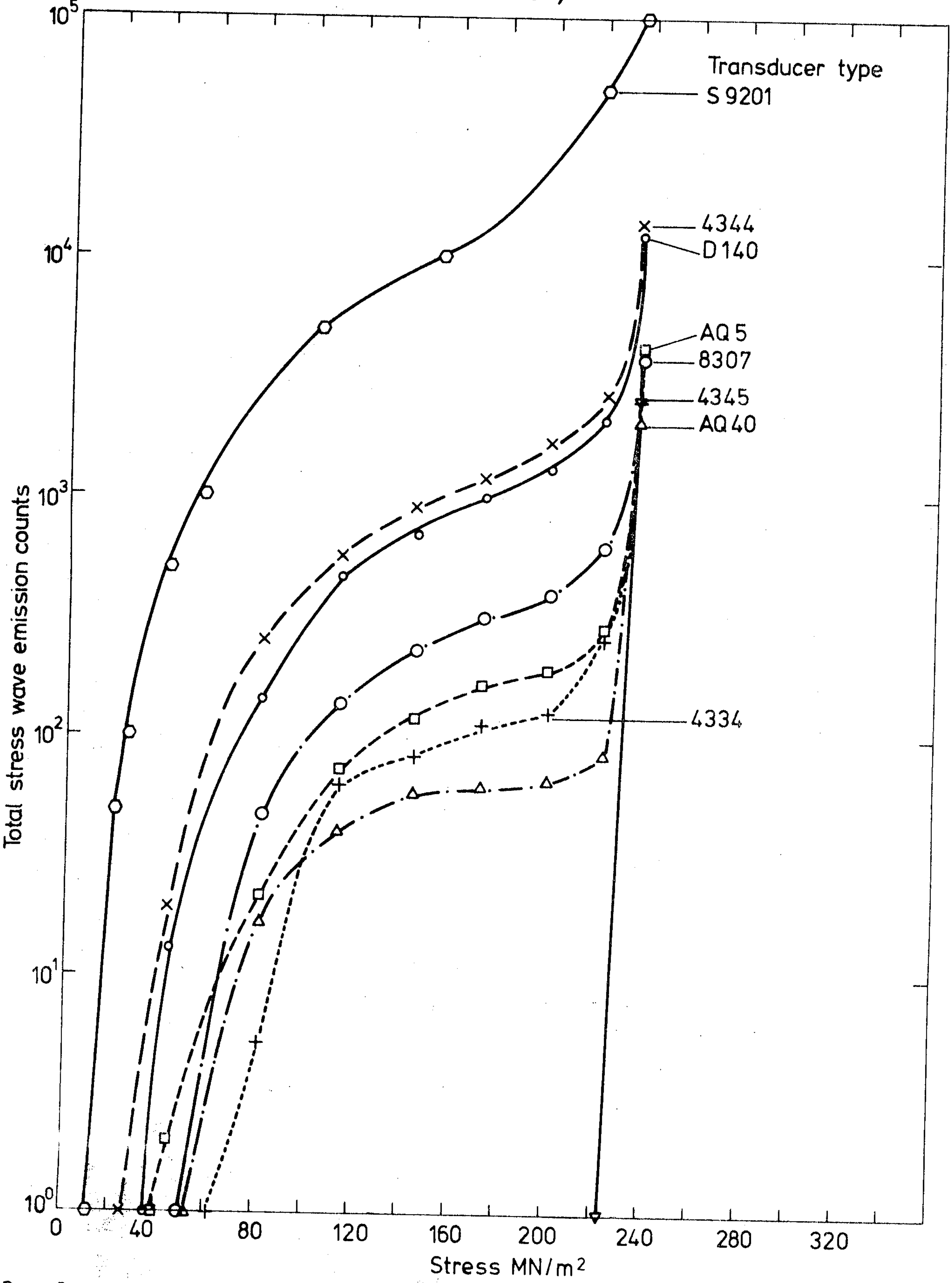

Fig.12 Comparison of SWE counts as a function of stress for the different transducers

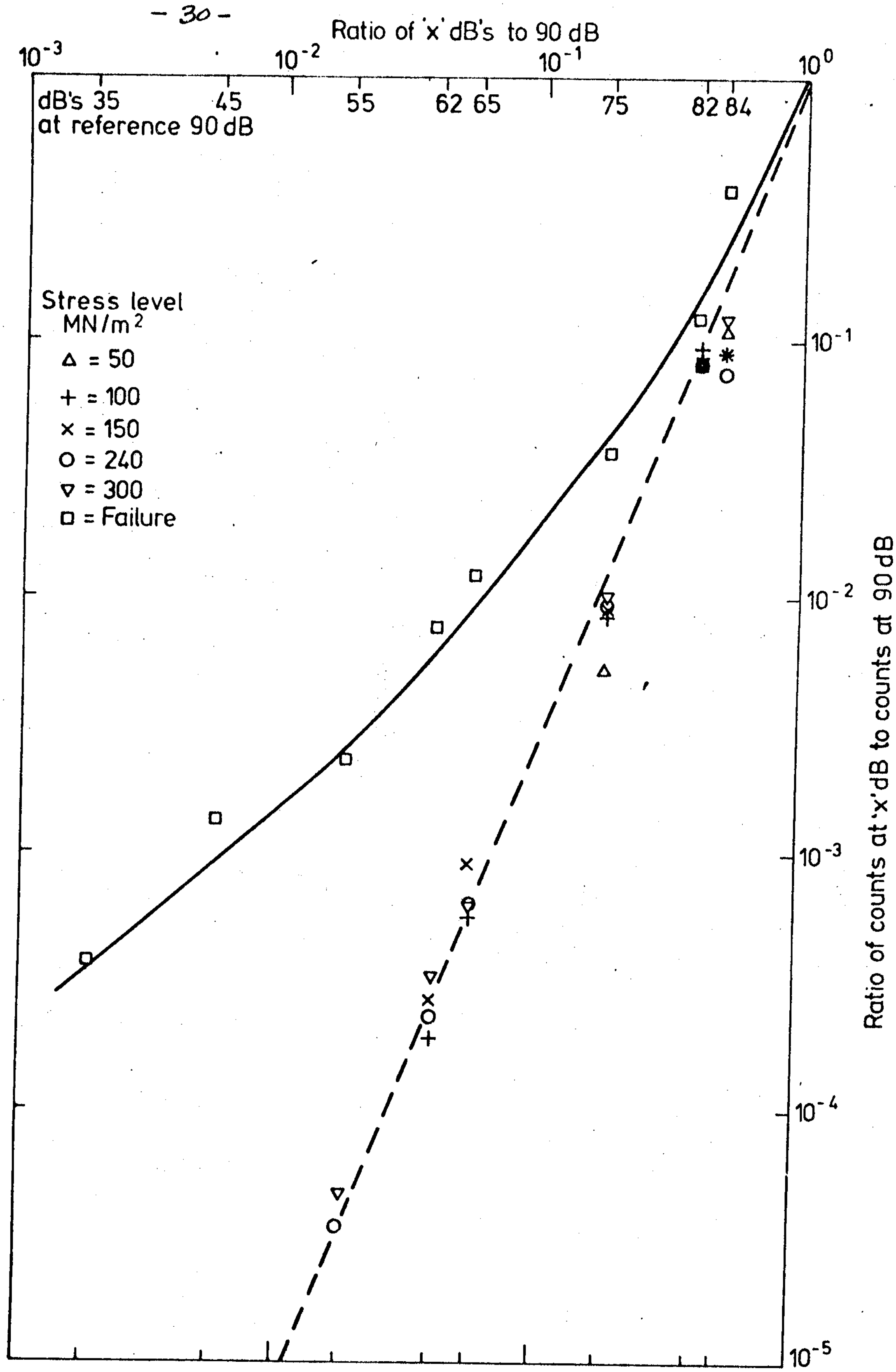

Fig.13 Relative count level as a function of relative gain level based on a reference point at 90 dB